Partial Lifetime Test of an SSC Collider Dipole

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Abstract— Over a period of ten months, a 15 m-long, 50 mm-aperture superconducting SSC Collider dipole was taken through a series of thermal and power cycles to check for changes in performance. One quench below operating current was experienced during this period. Small changes in the coil preload and certain harmonics were observed.

quenches are shown in this plot. The one training quench at 4.35 K occurred at the start of the third cold test period. The small variation in quench currents at 4.35K reflects changes in the helium temperature. Data from voltage taps indicated that the conductor-limited quenches occurred in the pole turn of the inner coil, as expected.

I. INTRODUCTION

The R&D program for the Superconducting Super Collider dipoles at Brookhaven National Laboratory culminated with the construction of seven full-sized models. Five of these were built by staff from the Magnet Systems Division of the Westinghouse Electric Corporation as backups for the SSC Accelerator Systems String Test (ASST). The construction and performance of these magnets have been reported previously [1-5].

One magnet, DCA213, was kept on the test stand for ten months. During this time it was subjected to a total of 67 thermal cycles [6], about 2000 power cycles to the 6.6 kA operating current [7], 40 conductor-limited, spontaneous quenches at 4.35 K or lower, and about 100 additional quenches from spot heaters, eddy currents, etc. The magnet was also operated successfully at reverse polarity, as a check on the suitability of the design for High Energy Booster magnets. The nominal SSC 25-year lifetime expectations for magnets are 50 thermal cycles, 100 quenches, and 20,000 power cycles [8].

A cross section of the magnet is given in Fig. 1. It is one of two ASST magnets that uses two layers of Kapton [9] for the turn-to-turn insulation of the cable [10], instead of the more traditional Kapton and epoxy-impregnated fiberglass.

II. QUENCH PERFORMANCE

The quench performance of the magnet is summarized in Fig. 2. For simplicity, only conductor-limited or training

Figure 1. Cold mass cross section for dipole DCA213.

III. AXIAL AND AZIMUTHAL FORCES

Azimuthal prestress measured at the pole of the coil, at room temperature and at 4.35 K (for $I=0$), is shown for the inner and outer coils in Fig. 3. The test periods at 4.35K are numbered. Within each test period, the initial one to three measurements were made before spontaneous quenching and the remainder were made after the quenching and various other types of tests. The predominant feature of the data is the (expected) prestress loss during cooldown. Another

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Figure 2. Quench history of the magnet. Operation at lower temperatures and at reverse polarity (RP) are noted separately. Thermal cycles (TC) are indicated by solid vertical lines; changes in temperature or polarity by dashed lines.

Figure 3. At one axial location, the average stress at the pole is shown for the inner (O) and outer (□) coils during each of the eight test periods at 4.35 K and during the intervening time at room temperature.

feature is the small decrease of prestress during a given cold test period. These two features were basically the same for each test period. In addition, there is a gradual loss of prestress for any specific state of the magnet, with the rate of loss decreasing in the later test periods (however, the inner coil prestress for test period #8 is slightly higher than for #7).

The cumulative azimuthal prestress loss from the second through the sixth test periods can be seen in Fig. 4, where the prestress is plotted against the square of the current, with $I^2 = 44 \text{ (kA)}^2$ for 20 TeV. Possible contributors to the prestress loss are time at room temperature or thermal cycling (90% of the power cycles occurred after the sixth cold test period).

The axial preload of the magnet ends is shown in a similar pair of plots: Fig. 5 for the end force as a function of cold test period, Fig. 6 for the end force as a function of I^2 . The end forces are higher at room temperature than at 4.35 K. The forces in the lead and nonlead ends for test periods four and later change gradually, but in opposite

directions. The end forces during magnet excitation are essentially the same for the second and sixth test periods.

The observed changes in prestress in the body of the magnet and preload in the ends are consistent with expectations based on thermal contraction coefficients and material properties. It should be noted that at 3.5 K, where these magnets were operated far above their normal operating field (Fig. 2), and no prestress remained at the pole, little or no training was required to reach the conductor limit.

Figure 4. Average inner and outer coil stress during magnet excitation, for the second and sixth 4.35 K test periods ($44 \times 10^6 \text{ A}^2$ corresponds to 20 TeV).

Figure 5. Total end force for the lead and nonlead ends with the same notation for the abscissa as Fig. 3.

Figure 6. Total end force during magnet excitation, for the second and sixth 4.35 K test periods.

Figure 7. The four lowest-order normal multipoles, in "units", averaged over the magnet straight-section, for six of the test periods of the magnet. The quadrupole is denoted $n=1$. Measurements were made at a central field of 2.1 T.

Figure 8. Skew multipoles, with the same notation as Fig. 7.

IV. FIELD QUALITY

For these magnets, the usual expression for the magnetic field is

$$B_y + iB_x = B_0 \sum_{n=0}^{\infty} (b_n + ia_n)(x + iy)^n$$

where x and y are the horizontal and vertical coordinates and B_0 is the dipole field strength. It is convenient to refer to the coefficients evaluated at a radius of 10 mm and scaled by $10^4/B_0$ as (dimensionless) "units." The a_n are the skew terms and the b_n are the normal terms. The quadrupole coefficients have $n=1$. The data reported here are integrals summed over the magnet's straight section measured in 1 m increments with a system that includes a rotating coil and a gravity sensor [11]. The magnet current was 2 kA (2.1 T). The measurements have been corrected for feeddown effects and are all made with the same rotating coil. The uncertainty in the scale is estimated to be about 5%.

Multipole measurements for six 4.35 K test periods are shown in Figs. 7 and 8 for the normal and skew coefficients respectively. In each test period the harmonics were measured at least twice in consecutive runs, so these pairs of runs give an indication of the short-term measuring uncertainty. In test period six, the harmonics were measured before and after (but not during) the period of negative polarity operation.

No systematic change is seen in five of the harmonics. There is a long-term drift of the normal sextupole b_2 , together with a step between cold periods two and three. A plot of the axial variation of b_2 for the initial and final runs shows the change to be uniform over the length of the magnet. The long-term drift is of the sign to be expected if the turns of the coils are gradually being compressed toward the midplane. (However, this is not directly caused by power cycles. The change in b_2 between periods six and eight is typical of the progression, while 90% of the power cycles occurred during this time.) Between the measurements of test periods two and three, the magnet was operated at 3.5 K and was at room temperature for two months. The total change in b_2 , about 0.06 units, is small compared to the systematic tolerance at high field, 0.8 units. Interestingly, an increase in a_3 of slightly more than 0.01 units occurred at the same time as the step in b_2 .

The skew quadrupole a_1 shows both a long-term decrease of about 0.02 units and a step decrease during period six of 0.04 units [12]. Along the magnet axis, the decrease in a_1 during period six occurs entirely in the magnet half toward the lead end. The principal event occurring during period six was operation of the magnet at reverse polarity. The magnetic forces don't change when the polarity is reversed. However, the iron hysteresis loop is quite different for unipolar and bipolar operation. If borne out by further tests, the change in a_1 would be important if it were systematic (tolerance 0.04 units) but negligible if it were random

(tolerance 1.25 units).

Within the measurement error (about 0.2 mrad), the axial variation of the dipole angle did not change during the test.

REFERENCES AND FOOTNOTES

- [1] C. Goodzeit et al., "Cold Mass Mechanical Design, Quench, and Mechanical Test Results for Full Length 50 mm Aperture SSC Model Dipoles built at BNL," Proc. XVth Int'l Conf. High Energy Accelerators, Hamburg, Germany, 1992, published in Int. J. Mod. Phys. A. (Proc. Suppl.) 2A, p. 584 (1993).
- [2] P. Wanderer et al., "Magnetic Design and Field Quality Measurements for Full Length 50 mm Aperture SSC Model Dipoles Built at BNL," *ibid.*, p. 641.
- [3] W. Nah et al., "Quench Characteristics of 5-cm-Aperture, 15-m-Long SSC Dipole Magnet Prototypes," IEEE Trans. Applied Superconductivity, Vol. 3, No. 1, March 1993, p. 658.
- [4] T. Ogitsu et al., "Mechanical Performance of 5-cm-Aperture, 15-m-Long SSC Dipole Magnet Prototypes," *ibid.*, p. 686.
- [5] Y. Zhao et al., "Current Dependence of Harmonic Field Coefficients of 5-cm-Aperture, 15-m-Long SSC Dipole Magnet Prototypes," *ibid.*, p. 674.
- [6] Nine of the thermal cycles were between room temperature and 4.35 K, 58 between room temperature and 70 K. Thermal cycles to 70 K were run as a background activity to other magnet testing. Since 97% of the thermal contraction of iron and stainless steel takes place by 70 K, the cycles to 70 K have essentially the same effect as cycles to 4.35 K.
- [7] Most of the power cycles were at 100 A/sec and 3.85 K, as compared to the Collider ramp rate of 4 A/sec at 4.35 K.
- [8] "Site-Specific Conceptual Design Executive Summary," SSCL-SR-1055 (July 1990) p. 31.
- [9] Kapton is a registered trademark of the Dupont Corporation.
- [10] M. Anerella, A.K. Ghosh, J. Schmalzle, E. Willen, "Improved Cable Insulation for Superconducting Magnets," 1993 Particle Accelerator Conference, Washington D.C., May 17-20, 1993 (to be published).
- [11] R. Thomas et al., "Performance of Field Measuring Probes for SSC Magnets," Proc. Fifth Annual International Industrial Symposium on the Superconducting Super Collider, San Francisco, CA, May 6-8, 1993 (to be published).
- [12] In principle, errors in correcting for the feeddown from b_2 to a_1 could be a spurious source of change, but given the small size of b_2 in the magnet and the lack of change in the centering distance for these runs, the amount of a_1 which could be due to centering errors is negligible.